Dehydration of Natural Gases via High Centrifugal Force

(Effect of Inlet Gas Velocity to Separation Efficiency)

by

Muhammad Afiq b. Mustaffa

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

July 2010

CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Lau Kok Keong)

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July 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am accountable for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD AFIQ B. MUSTAFFA

ABSTRACT

This project is executed to study the effect of inlet gas velocity to separation efficiency of removing moisture (free water) from natural gas. This experimental work had been executed at test rig specially build for this work and using high centrifugal compact separator. The project needs to prove that certain centrifugal equipment able to remove 99.9% moisture from natural gases. However this claim is made by hypothesis outcome from experimental work using solid particles of < 10 microns and SF6 as the carrier gas. There are no theoretical studies and prove regarding this matter. This project varies the inlet gas velocity of the centrifugal separator at fixed temperature which is 35°C and water loading 20%. The experimental work required specially fabricated compressor that allow set up pressure range from 10 bar to 70 bar. The gas flow with desired pressure and compressor speed (%) enters spraying system that injected fine water droplets (< 10 microns) to the gas line. Wet natural gases flow into the centrifugal compact separators to separate free water from natural gases. Water collection will determine the separation efficiency of the equipment based on the operating conditions. Higher pressure will generate higher inlet velocity of gas and this will produce higher force into the separator. This force helps creating higher centrifugal force which improves water separation from natural gases.

ACKNOWLEDGEMENT

I am extending my warm appreciations to all of those who have contributed either directly or indirectly to the completion of this dissertation. I would like to thanks my supervisors, Dr. Lau Kok Keong for the guidance during the project and Ms. Norhayati Mellon for the assistance on the experimental work. This project will not be completed without the help from both of you. Thank you to my colleagues and my friends who always been there for me during the up and down of the project. My family who give me support the whole time from the start of the project.

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ABBREVIATIONS AND NOMECLATURES

A = *cross sectional area*

D = *diameter*

g = *acceleration of gravity*

P = *pressure*

q = *volumetric flow rate*

r = *radius*

v = *velocity*

ρ= *density*

CHAPTER 1

INTRODUCTION

The petroleum industries nowadays are looking for efficient and profitable system for dehydration of natural gases. This industry has to move rapidly to find method to separate multiphase flows which are cost and space ineffective considering large floating facilities for process equipment equates to larger platform area and support structure. This critical aspect has pushed this energy industry for compact separation technology development.

This new technology are becoming more accepted as alternative for dehydration method to traditional separator as they are more lighter in weight, require little maintenance, easy to install and able to operate under minimal supervision. Presently, there are several platforms are using compact separator but not as the main natural gas dehydration system but only auxiliary system to reduce the moisture (free water) content in order to lessen the separator capacity for durability purpose. Reducing cost significantly require improvement on the centrifugal compact separator more on the performance so that it is economically justified.

This paper will study one of the parameters that contribute on the separation efficiency of this centrifugal compact separator to eliminate 99.9% of moisture (free water) from natural gases. The parameter that interest the author is the effect of inlet gas velocity on separation efficiency at mixed temperature 35°C, pressure at 60 bar, 50 bar and 40 bar with 20% water loading. The inlet gas velocity which directly related to the compressor speed will have a significant effect on the separation efficiency as different speeds will result in certain mass flow which contributes in the separation process of moisture (free water) from the natural gases.

For this experiment, a test rig has been build with desired specification similar with real platform used for dehydration system of natural gases. The test rig has several sections which includes water and gas storage unit, spraying system, adsorption system, centrifugal compact separator and compressor.

The compressor will compress the natural gas by increasing the pressure to desired setting (e.g. 40 bar). The water tank that connects to a pump was installed with flowmeter to control the amount of the water added into the spraying section and heating system to increase the temperature so that the mixed temperature of water and natural gas will be 35°C. This water addition stage was executed after the natural gas flowrate is stable. The test rig was left operated for about half an hour before water collection stage take place. The separation efficiency is simply comparing the amount of water added into the system and the amount of water collected at the end of experiment. This experiment was repeated several times at different compressor speed to study the effect of gas inlet velocity toward the separation efficiency.

In chapter 2 of this paper the possibilities and past research on centrifugal separation is being discuss regarding the fundamental operation of the separator. Chapters 3 discuss the methodology of the experiment and in chapter 4 result of the project are presented with discussion. Chapter 5 will conclude the project works and provide some recommendation for future work.

1.1 Background

Natural gas is an important source of main energy where usually found in subsurface rock reservoirs which are often associated with crude oil. Natural gas generally contain hydrocarbon primarily methane. Table 1 provides the typical composition of natural gas.

Table 1: Composition of Natural Gas

Components		Compositions (%)
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	0-20%
Butane	C_4H_{10}	0-20%
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

1.1.1 Natural Gas Separation Flow

Transportation of gas involves several steps before continue being process at the onshore facilities. The gas should be dehydrated and free from any contamination in order to avoid major transportation problems involving the pipelines. Figure 1 is a schematic overview of gas separation steps before transport to onshore.

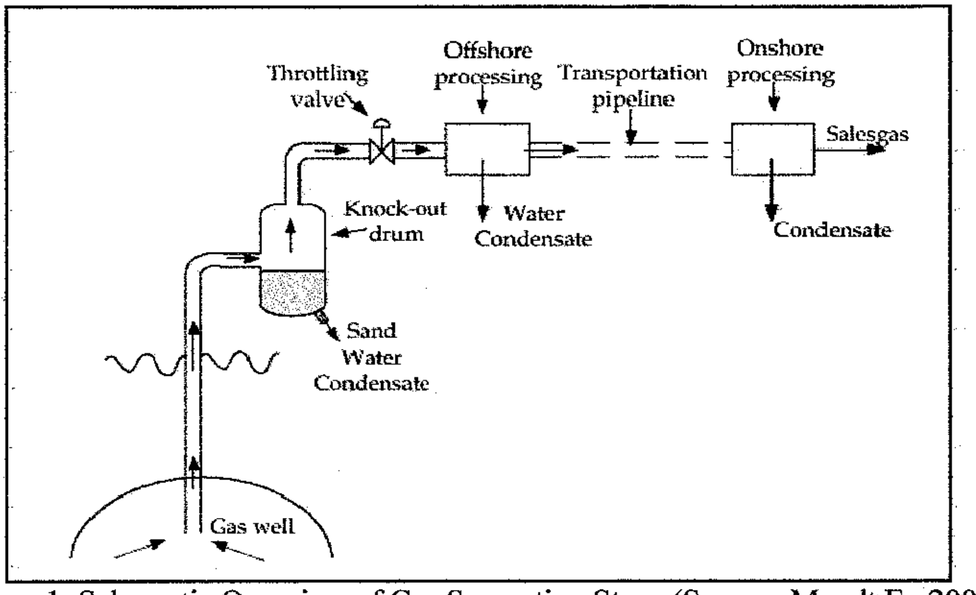


Figure 1: Schematic Overview of Gas Separation Steps (Source: Mondt E., 2005)

Therefore the offshore platforms are built to remove those contaminants from the gas to ensure no major problem during transportation especially on pipeline. Then the natural gas is further processes to meet sales gas requirement. Sales gas is an arrangement made between the company producing the natural gases and the pipeline company for the quality of the gas the purchaser will accept (John J. Carrol, 2009).

Natural gas that is extracted from a reservoir reaches the surface is transferred by a high- pressure pipeline into a tank that act as the conventional separator. This gravity settling method is to separate the heavier solid contaminants and liquid that condensed. After that, the pressure is reduces to ease transportation process of the natural gases. The pressure is reduced by the throttling valve which results in reducing pressure and also the temperature.

These temperature drops will condense the hydrocarbon vapors and water vapor. This stage is where the dehydration of the natural gases takes place before the gas is brought to the required specifications for pipeline transportation to the onshore facilities.

1.1.2 Pipeline Specification for Natural Gas

Table 2 gives the typical pipeline specification for natural gas (Jaffret, 1997; Kidnay and Parrish, 2006; Manning and Thompson, 1991).

Table 2 : Typical Specification for Pipeline Natural Gas

Characteristics	Specifications
Water content	4 – 7 lb/MMscf (60 – 110 mg/m3)
Hydrogen sulphide content	0.25 – 0.3 g/100 scf (6-7 mg/m3)
Carbon dioxide content	1-3 mole%
Gross heating value	950 Btu/min (35,400 kJ/m3)
Total sulphur content	5-20 g/100 scf (115 – 460 mg/m3)
Oxygen content	1 mole %
Solids	Free of particulate solids

Under normal production, natural gas conditions are saturated with water vapor. These water vapor increases the natural gases' corrosiveness especially with the present of acid gases. Several methods can be used to dry natural and four of the most common are glycols, regenerative adsorption systems, membrane filters and deliquescent, commonly referred to as dry bed desiccants.

1.1.3 Current Natural Gas Dehydration Method

Nowadays there are several dehydration method widely used for natural gas dehydration process. The method are includes using liquid desiccants (glycol absorption), solid desiccants (adsorption), expansion refrigeration (low temperature separation) and deliquescing desiccants (calcium chloride). Table 3 gives the information on the advantages and disadvantages of the current dehydration method (Mellon, N., 2008).

Table 3: Technical Capability, Advantages and Disadvantages of Conventional Natural Gas Dehydration Techniques

Separation method	Technical capabilities and advantages	Disadvantages
Glycol absorption	1. Established and widely accepted method 2. Able to achieve final water content of 60 ppmv	1. Requires constant monitoring to minimise operational problems (glycol losses, foaming, glycol degradation etc) 2. Environmental problem associated with BTEX emission 3. High capital cost due to requirement of associated equipment
Adsorption (solid desiccant)	1. Able to reduce final water content to 0.1 ppmv. 2. Reduce capital cost (less associated equipment) 3. Minimal BTEX emission	1. Hydrothermal damaging of adsorbent 2. Impurities in feed gas causes bed contamination leading to poor performance 3. Incomplete regeneration leads to premature breakthrough
Adsorption (deliquescing desiccant)	1. Closed system, no BTEX emission 2. No heating requirement for regeneration, thus an added safety factor	1. Waste product in the form of brine and considered as oilfield brine.
Expansion refrigeration	1. Able to remove water from natural gas stream to very low value	1. Needs glycol injection to prevent hydrate formation

1.2 Problem statement

This project are been executed due to claim made on the capability of certain centrifugal equipment in removing moisture (free water) from natural gas. However, most of the data reported on the moisture (free water) removal from natural gas is referred on hypothetical outcome from experiments that had been done using solid particles of < 10 microns using SF6 as the carrier gas (operating pressure of 10 bar or less). There are no proved and establishment from the theory on its credibility to perform separation work eliminating up to 99.9% moisture (free water) from natural gases. The study will cover the factors that affecting the separation efficiency of moisture (free water) from natural gases.

1.3 Objective and Scope of Studies

This research is carried out to study the factors that influence the separation efficiency of moisture (free water) removal from natural gas using centrifugal forces. The author's objective is

- To study the effect of inlet gas velocity on separation efficiency at mixed temperature 35°C, 20% water loading and at various pressures; 60 bar, 50 bar and 40 bar.

The inlet gas velocity which directly related to the compressor speed will have a significant effect on the separation efficiency as different speeds will carry different amount of energy which contribute in the separation process of the moisture (free water) from the natural gases. The pressures selected are due to limitation of the equipment performance.

CHAPTER 2

LITERATURE REVIEW

Improvements on the centrifugal compact separator are essential in order to lower down the capital cost. Compact separation is both necessary and unavoidable because it provides benefits to separation design beyond minimal facilities especially on the space and weight savings (C.H. Rawlins, 2003). This is because large floating facilities for process equipment equates to larger platform area and support structure which increasing the economic factor. In addition the weight saving simplifies equipment transport and installation, both onshore (factory to terminal) and offshore (terminal to platform to deck).

Mondt E. (2005) agrees that the offshore gas well required improvement of current separation technique that commonly used separators gravity to separate the dispersed phase. The increased of liquid contamination that keep the well under pressure has increase the capacity of these separation equipment and the current devices is no longer sufficient. As a result, heavier separation devices are needed which contribute to more expensive supporting structures that are not economically viable. This has pushed the petroleum industry to change to compact separation and start developing and improving this new technology to ensure it will able to execute the separation with better performance so that it is economically justified.

Motion tolerance is also the benefits using centrifugal compact separation equipment. On all floating systems especially FPSO based, wave motion always causes a corresponding wave motion in separating vessels that leads to process upsets, spurious alarm trips, and most importantly poor separation performance. With compact separation unit such as cyclonic and rotordynamic, the weather does not affect the dehydration process as it operate mostly at 10 to 5,000 times gravitational acceleration (C.H. Rawlins, 2003). This motion insensitive characteristic allow the equipment to operate equally well under static or moving conditions.

C.H. Rawlins (2003) compared the gas-scrubbing method between gravity settling drum, impact vane pack, cyclonic axial-flow cyclone and rotordynamic IRIS. By experiment, 10-μm water droplet from a methane stream at 1,350 psig and 100 MMscf/d flow rate should be removed. From the Table 4, cyclonic axial-flox cyclone and rotordynamic IRIS have 99.99% performance compare to gravity settling drum and impact vane pack which have 31% and 81% performance respectively. The diameter, length and weight clearly indicate that high centrifugal equipment offer smaller size of the equipment and lighter compare to large gravity vessel. The process cost, however, is a higher due to high pressure drop and maintenance.

Table 4: Comparison of Gas-Scrubbing Methods

Force Equipment	Gravity Settling Drum	Impact Vane Pack	Cyclonic Axial-Flow Cyclone	Rotordynamic IRIS
Performance (removing a 10-μm droplet), %	31	81	99.9	99.99
Diameter, in.	60	36	30	27
Length, in.	180	90	114	36
Bare weight, lbm	30,875	9,664	8,890	1,577
Operating weight, lbm	33,270	10,409	9,383	1,600
Pressure drop, psi	0.2	0.6	1.9	46.6

J.J.H Brouwers (1996) also compared several methods that exist to perform separation process. Each of the method he studied is based on application of specific physical principles and each of them has its advantages and disadvantages.

Table 5: Mechanisms and Indications for Working Range, Fixed Costs and Variable Costs of Techniques for Separating Particles from Gases

	Mechanism	Working range d_p > (μm)	Fixed costs	Variable costs
Gravitation chamber	Gravitational force	100	Low	Low
Cyclone	Centrifugal force	5	Low	Medium
Rotational particle separator	Centrifugal force	0.5	Medium	Medium
Venturi scrubber	Inertia, interception, diffusion	0.2	High	High
Fabric filter	Inertia, interception, diffusion	0.01	High	High
Electrostatic precipitator	Coulomb force	0.01	High	Low

From the table, the equipment that uses centrifugal force as the mechanism to separate the multiphase are resulting in cost saving and wider working range as it can separate small particle that up to 0.5μm. Compact separator emerges to meet most of the factor listed to be the new dehydration technology. It is simple, compact, possess low weight, low-cost, require little maintenance, and are easy to install and operate (S. Wang *et al.*, 2000).

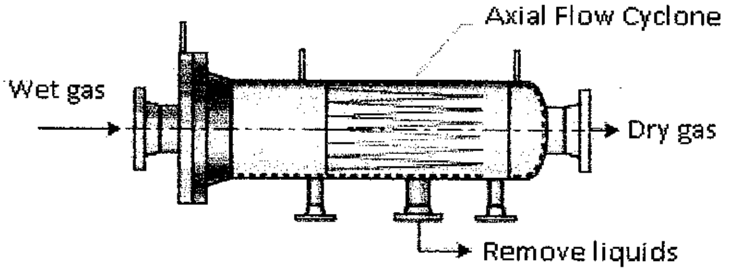


Figure 2: Basic Principle of Cyclonic Axial-Flow Cyclone

The basic operating principle of centrifugal compact separation is as shown on figure above. The natural gas that contain moisture (free water) will enter as inlet and the separation process happen inside the compact separator where the axial flow will create high centrifugal force. The energy created depends on the inlet velocity of the wet gas. Theoretically, higher inlet gas velocity will result in more angular speed which leads to more liquid removed from the bottom of the equipment. The gas leaves the compact separator as dry gas.

This centrifugal separation equipment operates using different energy to increase separation forces beyond standard gravitational acceleration. As example cyclonic devices derive energy from the system pressure to be converted to pressure drop as it is proportional to density difference of the separated phases. A large density differential, such as water and gas or sand and water, may require only 2- to 25-psi pressure drop. However, such as oil and water that have small density differential, may required 50 to 250 psi pressure drop (C.H. Rawlins ; 2003).

$$v_t = \frac{\omega^2 r D_p^2 (\rho_p - \rho)}{18\mu} \qquad [1]$$

Equation 1 is from to the Stokes law equation which relates the density with the settling velocity of the particular particle. Settling velocity indicate the degree of difficulties for certain molecule to be separated. The higher value of settling velocity will result in easier separation process to take place. From the density, we can conclude that free water is easier to be separated from natural gas compared to water vapour. The density of water vapour is calculated by assuming the validity of ideal gas law as given in Equation 2.

$$\frac{mass}{V} = \rho = \frac{P \times M.W}{RTZ} \qquad [2]$$

From this equation, the molecular weight gives significant impact on the value of density which leads to the settling velocity that indicates the ease of separation from the natural gas. As example between carbon dioxide and methane, the separation of those two gases are possible as the difference of molecular weight are significant compare to methane and water which have small difference of the molecular weight (Mellon, N., 2008).

Separation of particles in the rotational particles separator (RPS) is well-defined and quantifiable physical process (J.J.H Brouwers, 1996). This is different type of separator which use filter element to separate the component from natural gas. This RPS study are only focusing on particles more than 0.1 μm and larger from gases. This rotating filter element consist of a multitude of axially oriented channels which rotating as a whole around a common axis.

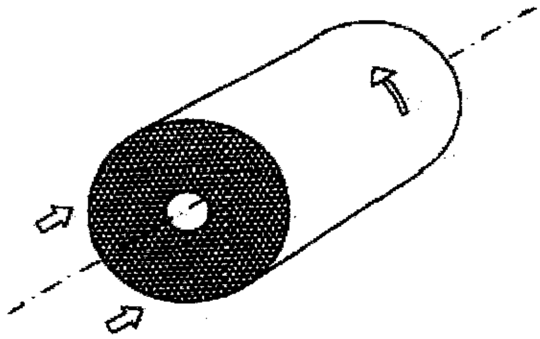


Figure 3: Filter Element of the Rotational Particle Separator

(Source: J.J.H Brouwers, 1996)

Equation 3 is also Stokes law equation that represents the drag force describes the resistance due to relative motion between particle and gases. The theoretical expressions for the particle collection efficiency is a function of particles diameter by also considering the channel shape, velocity profile, flow distribution, and effects of molecular movement with assumption that uniform axial velocity over the channel cross-section,

$$d_{p100\%} = \left(\frac{18 \eta w_{gas} d_c}{\rho_p \Omega^2 r L} \right)^{1/2} \qquad [3]$$

By decreasing the radial position (r), the constant value; d_c, w_{gas} and L, $d_{p100\%}$ will increase. To maintain the value of $d_{p100\%}$, value of w_{gas} should be increased linearly with distance r from rotation axis. As a result, the degree of particle separation will be same for all channels. Compact separator often rely on the centrifugal force are dependent on the inlet geometry of the channel (Barbuceanu, N., 2001). The particle collection efficiency relates with the shape of the channel; triangle, circle, concentric rings and sinusoids as shown at Figure 4.

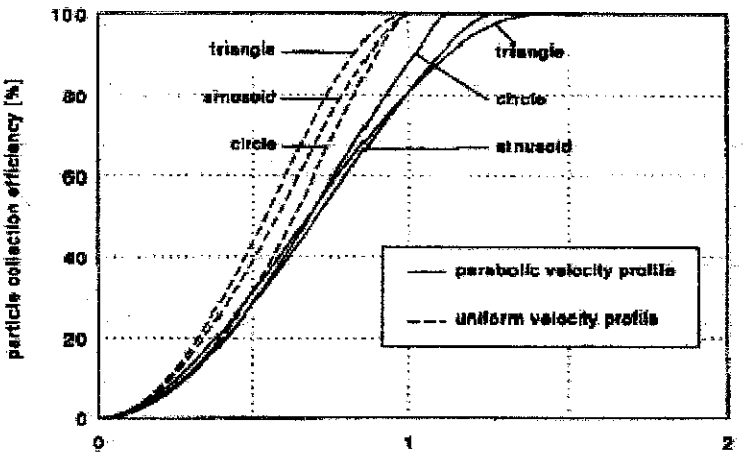


Figure 4: Collection Efficiency (%) Vs Channel Shape

(Source: J.J.H Brouwers, 1996)

From the figure, triangle shape with uniform velocity profile has higher particle collection efficiency. But for parabolic velocity profile, channel's shape of circle is more convenient to result on higher particle collection efficiency. Although this report does not discuss on the shape of the channel, it is important during the designing stage to ensure higher separation efficiency removing moisture (free water) from natural gas.

Application of this high centrifugal compact separator is not only limited to the dehydration process. In fact, there are several other processes that seek and executed feasibility study regarding the compact separation. Another process that used high gravity technology is including carbon dioxide (CO_2) removal. Carbon dioxide is the major greenhouse gas of which emissions need to be reduced. This greenhouse gas is most likely responsible for the increase of earth temperature. Reducing CO_2 content is essential to reduce this greenhouse effect.

This CO_2 is being done by absorption in a rotating packed bed (RPB). The study of the removal of CO_2 from a flue gas is limited for gas containing 1-10 mol % of CO_2 by absorption in a RPB. The experiment includes varying the rotating speed and relates the parameter with mass transfer efficiency.

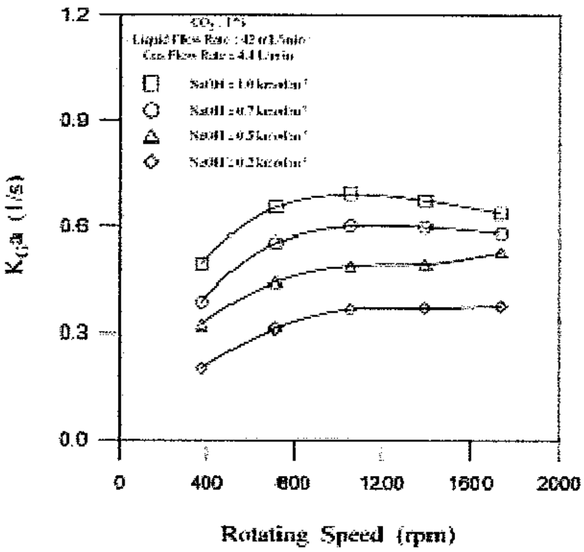


Figure 5: K_{Ga} vs. Rotational Speed Graph (rpm)

The results indicated that a rotating speed higher than 1000 rpm was required to achieve high mass-transfer efficiency, (s^{-1}), K_{Ga}. It is seen that K_{Ga} was increased with an increase in the rotating speed in the range from 375 to 1000 rpm, indicating that the mass-transfer resistances were reduced with an increase in the rotating speed (Chia-Chang Lin *et al.*, 2003). Manipulating the rotating speed (which in the author project is manipulating the compressor speed; 60%, 80% and 100%) generally does give significant effect on the mass-transfer or flowrate that relates to the separation efficiency of the process.

CHAPTER 3

METHODODLOGY

3.1 Experiment Facility

For this experiment, a test rig has been build with desired specification similar with real platform used for dehydration system of natural gases. Figure 6 is the P&ID of the test rig.

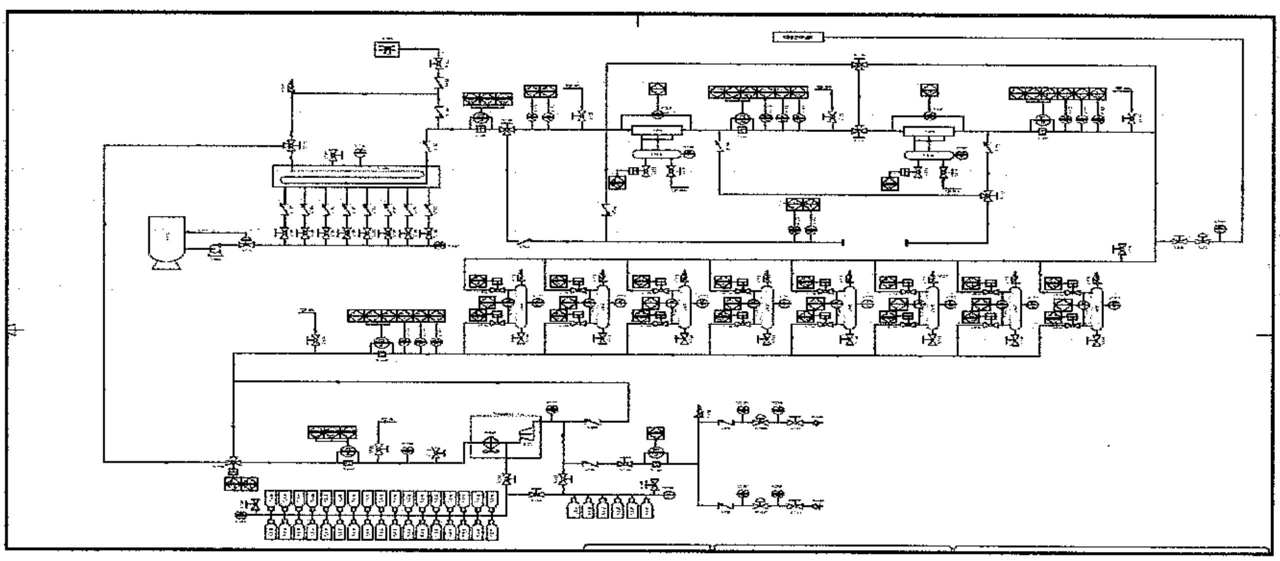


Figure 6: P&ID of the Test Rig

This test rig has several sections which includes water and gas storage, compressor, spraying system, water tank collection, adsorption column and compact separator.

Water Storage

This tank connects to a pump before entering the spraying system. This tank also equip with heating system to achieve certain preferred temperature setting. The setting for water temperature can varies up to 50°C.

Gas Storage

The optimum gas pressure inside the storage should be high and sufficient before running the experiment. This to ensure the desired pressure can be archive to obtain certain data for different value of pressure as if pressure is the parameter the need to be studied.

Compressor

This compressor is specially fabricated to meet the demand of this project. The compressor able to offer operating pressure from 10 bar to 80 bar with various compressor speeds; 60%, 80% and 100%. The operating temperature is up to 45°C.

Spraying System

The spraying section consist more than 10 nozzles that able to produce fine droplets (less than 10 micron) to be injected into the gas stream.

Water Tank Collection

This water tank collects water after drainage process from the separator. After shutdown the compressor, the drainage process take place to measure the water collected after the separation take place.

Adsorption Column

This column install to ensure the moisture content inside the gas stream is within allowable amount to avoid wet gas entering the compressor. High moisture of the gas stream entering the compressor caused damaged and equipment malfunctions.

Compact Separator

This high centrifugal compact separator is design to eliminate 99.9% moisture (free water) from natural gases. The wet gas that enters this separator as inlet enables contact with the rotating blade inside the compact separator. The collected water droplets are separated at the bottom part of the separator entering a knock out drum. This high centrifugal compact separator is able to withstand inlet pressure up to 80 bar and the speed can reach up to 4000 rpm.

3.2 Experiment Run

Before wet run experiment executed, there must be a benchmark of the experiment. The experiment starts with dry run calibration. This dry run calibration executed to set the baseline for the project. 'Dry run' indicated that no water was involved in this experiment. Table 6 is the list of experiments that should be executed. All these parameter need to undergo dry run calibration before any water addition involve in the experiment.

Table 6: Experiments Parameters

Pressure (bar)	Water Load (%)	Compressor speed (%)	Mixed Temperature (□c)
60 bar	20	100	35
		80	35
		60	35
50 bar	20	100	35
		80	35
		60	35
40 bar	20	100	35
		80	35
		60	35

The set up of this experiment needs to be done in sequences to avoid any slip or experiment error. The compressor is run for several minutes at 10 bar to get the initial data of the gas moisture content and level of the knock out drum. The experiment proceeds to pressure increase to desired set point. The system is left stable for half an hour to ensure separation time process is sufficient. The necessarily data is recorded including the separator reading, moisture content, temperature and gas mass flow. The pressure of the compressor reduced periodically and shutdown.

A similar set-up is used for wet run experiment. During the time for the system to stable, the temperature of the gas and water inside the water tank is recorded. The wet run data sheet should be filled before, during and after water addition to the gas stream. This is to ensure sufficient data is retrieve before the water added and also the changes to the data when the water loaded to the system and be able to compare the difference before and after the water loading to the system in order to study the effectiveness of the separator equipment. When the mixed temperature is 35°C, the water addition stage may take place. From the flowmeter, the initial and final reading is recorded to identify amount of water injected into the gas stream. After shutting down the compressor, water purging step from the knock out drum can start. From the water tank collection, record the amount of water after the experiment executed.

3.3 Separation Efficiency

From the water collection, we can calculate the separation efficiency to compare the difference of the separation with regard to the compressor speed. We are concerned with the feed, denoted as F, the collected particle, C and the discharge fraction, D. The mass balance can be expressed by:

$$F = C + D$$

Thus, the efficiency can simply be expressed as:

$$\textit{Efficiency, } \eta = \frac{\textit{Amount of water collected in water tank, C}}{\textit{Amount of water injected into the system, F}}$$

The efficiency is measured by percentage

$$\eta = \frac{C}{F} \times 100\% = \frac{C}{C+D} \times 100\%$$

Table 7: Experiment Schedule

Experiment	March				April				May				June		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pressure 60 bar, Compressor Speed 100%, Liquid Loading 20%, Mixed Temperature 35°C.															
Pressure 60 bar, 40 bar, Compressor Speed 80%, Liquid Loading 20%, Mixed Temperature 35°C.															
Pressure 60 bar, Compressor Speed 60%, Liquid Loading 20%, Mixed Temperature 35°C.															
Pressure 50 bar, 40 bar, Compressor Speed 100%, Liquid Loading 20%, Mixed Temperature 35°C.															
Pressure 50 bar, Compressor Speed 80%, Liquid Loading 20%, Mixed Temperature 35°C.															
Pressure 60 bar, 40 bar, Compressor Speed 60%, Liquid Loading 20%, Mixed Temperature 35°C.															

CHAPTER 4

RESULT AND DISCUSSION

In this chapter, results are presented. The conditions that been used for the experiment; mixed temperature, pressure and water loading is already stated in chapter 3. Since the experiment have start since last semester, the progress of the experiment is completed as schedule. Some of the results are already obtain and some of the data need to redo due to some error during the experiment. Below is the experiment data that have been complete under my scope of study.

Table 8: Experiment Data

Pressure (bar)	Water Load (%)	Compressor speed (%)	Gas Mass Flow (kg/hr)	Gas Density (kg/m3)	Volume Flow (m3/hr)	Efficiency (%)
50 bar	20	100	2367.4367	31.94	74.12137445	96.078431
		80	1955.9067	31.51	62.07257061	94
		60	1297.203	40.71	31.86448047	86.44
60 bar	20	100	2194.26	35.595	61.64517488	95.25
		80	2225.4033	36.76	60.53871872	94
		60	1764.9433	39.07	45.1738751	90.28571
40 bar	20	100	1766.185	24.4	72.38463115	93.33
		80	1232	25.56	48.20031299	80
		60	1051.1967	24.06	43.69063591	52

From the data above, interpretation should be made by plotting graph from the data gained to seek for the relationship of the inlet gas velocity with separation efficiency. Since the author work are focusing on the various inlet velocity which manipulated by the compressor speeds, the data is converted in volumetric flowrate. The speed of the compressor should determine the volumetric flowrate of the inlet gas velocity. This is verified by Figure 7 below, the gas flowrate are increasing as the compressor speed increase to 100%. The pattern also consider the operating pressure that been used as higher pressure gives higher volumetric flowrate.

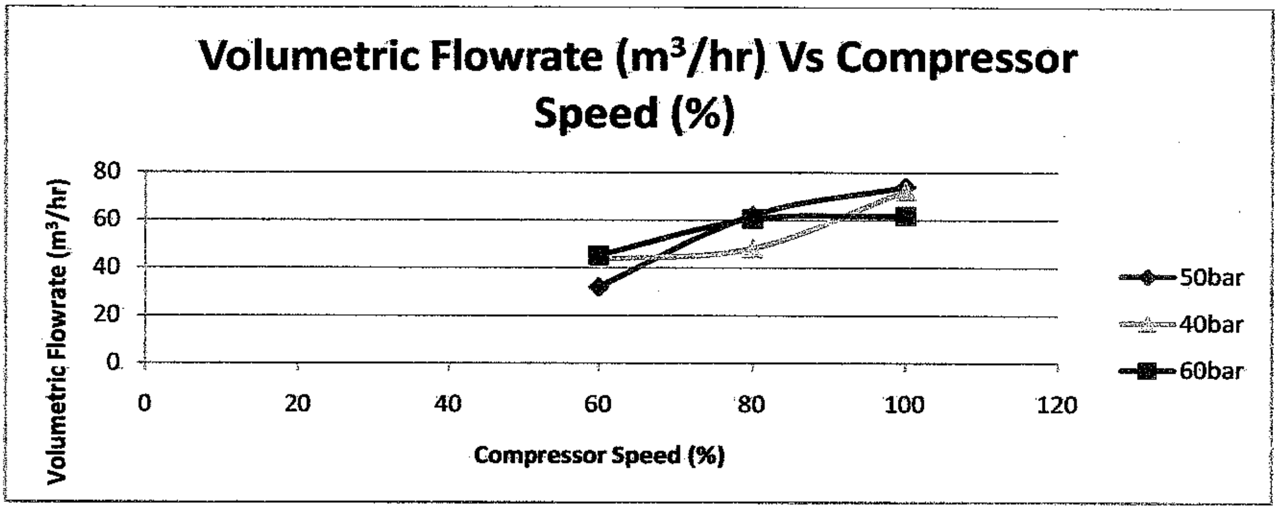


Figure 7: Volumetric Flowrate (m^3/hr) Vs Compressor Speed

The volumetric flowrate for all operating pressure increases exponentially with the compressor speed. Higher pressure supplied more energy to the flow which increasing the gas flowrate. Some data seems to result in different behavior. As example gas pressure at 50 bar does increase following the trend unlike gas at pressure 60 bar which increase from compressor speed 60% to 80% but the flow remain constant although at 100% compressor speed. This is because the pressure at the gas feed tank is not sufficient during the experiment to achieve desired pressure which result in having lower volumetric flowrate of the inlet. From this relationship we further seek effect of the inlet velocity to the separation efficiency as the main objective of this project.

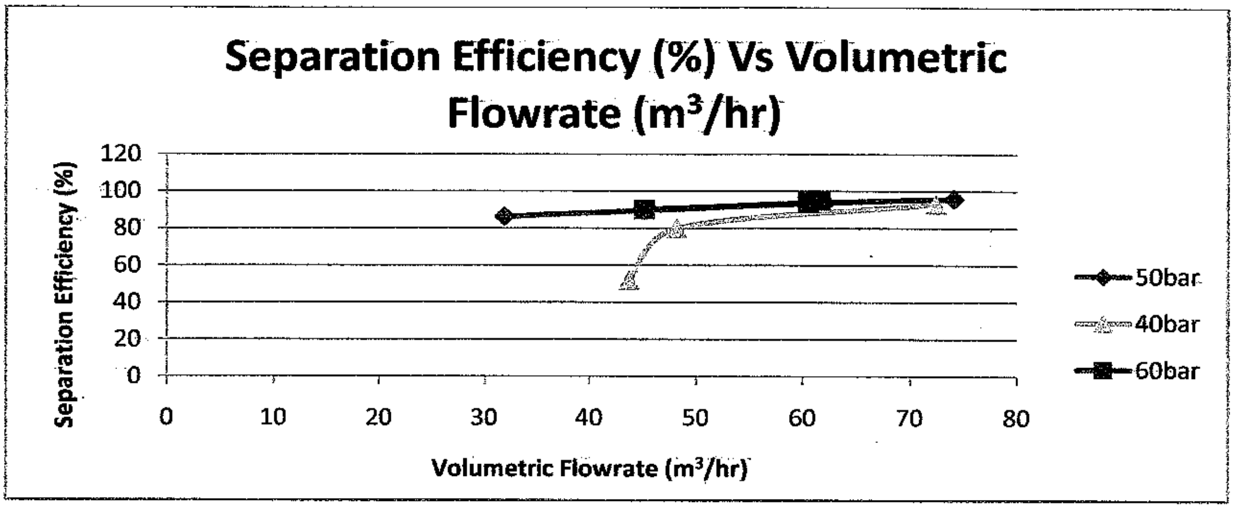


Figure 8: Separation Efficiency (%) Vs Volumetric Flowrate (m^3/hr)

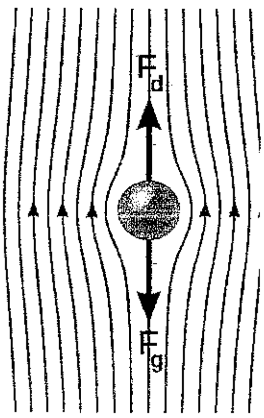


Figure 9: Creeping Flow past a Sphere

From Figure 8, separation efficiency for 50 bar increase at the higher volumetric flowrate, these trends also apply for gas at 40 bar. Gas at pressure 60 bar which is the highest pressure does not result in higher separation efficiency. This is because the volumetric flowrate is lower than other at 100% compressor speed (Please refer Figure 7). To explain further on the effect of inlet gas velocity to the separation efficiency, Stoke law is used. Stoke law or drag force is exerted on spherical objects with very small Reynolds numbers (e.g., very small particles). These apply on the experiment as the particle created by the spraying system is less than 10 micron and assuming the flow inside the gas piping are laminar flow, Stoke law are applicable and relevant for this experiment.

$$F_d = 6\pi\,\eta\,R\,V \tag{4}$$

Equation 4 shows the relation between drag force, f_d and force by gravity, f_g. The particle velocity, V gives significant impact on the drag force. From this Stoke law, when the particles are falling by their own weight due to gravity, then a settling velocity, is reached when this frictional force combined with the buoyant force exactly balance the gravitational force. This is where the velocity of the particle does not increase anymore. The resulting settling velocity is given equation 1.

Since the droplets present in the flow are very small in size which is less than 10 microns, inertia forces that act on them are very small. We can assume that the particles follow the streamlines. This is an exception for the radial direction where, as a result of centrifugal and buoyancy forces, they move relative to the fluid (Mond.E and Kemenade, E., 2003). The radial particle velocity v_p can be calculated from the equilibrium between centrifugal, buoyancy and drag forces acting on the particle. This equation is similar with settling velocity which different type of velocity. The radial particle velocity can be calculated using equation 5 below.

$$v_p = \frac{(\rho_f - \rho_p) d_p^2 \Omega^2 r}{18 \eta_f}$$

[5]

From the equation, ρ_p is the dispersed phase density, ρ_f the fluid density, d_p the particle diameter, Ω the angular speed, r the radius and η_f the dynamic viscosity of the fluid.

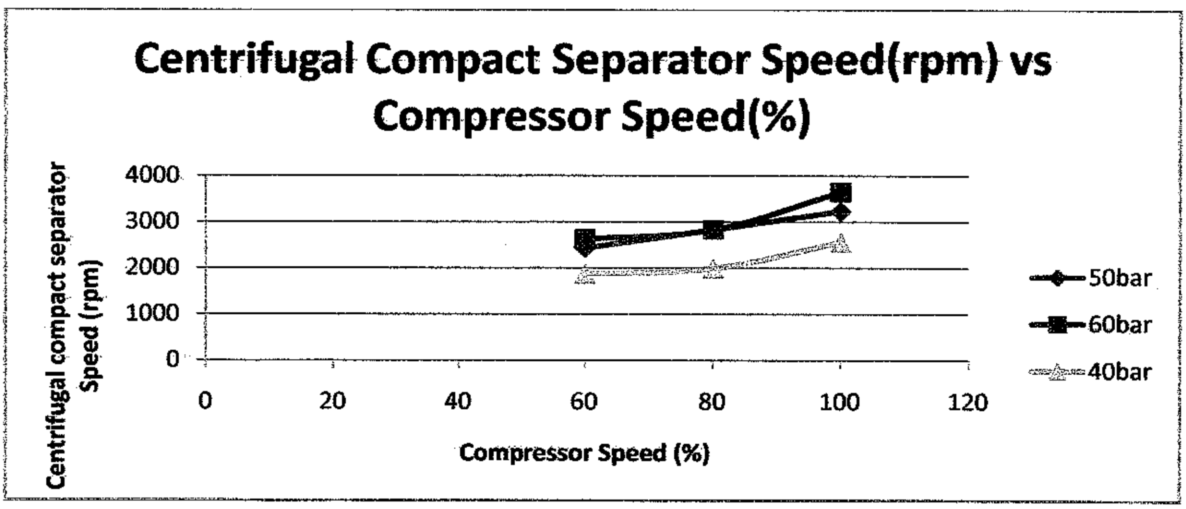
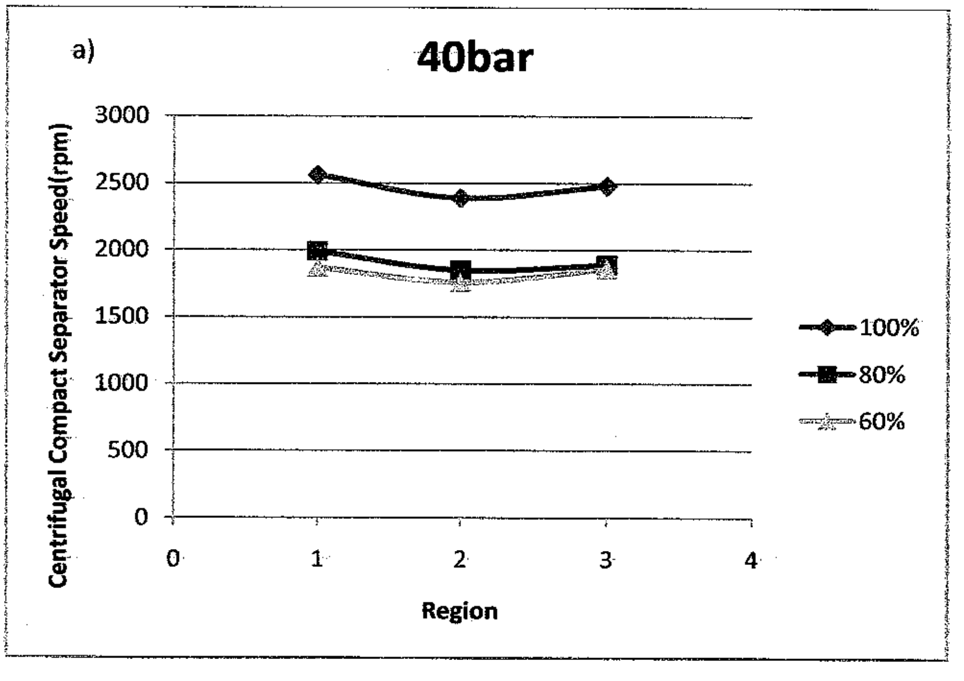
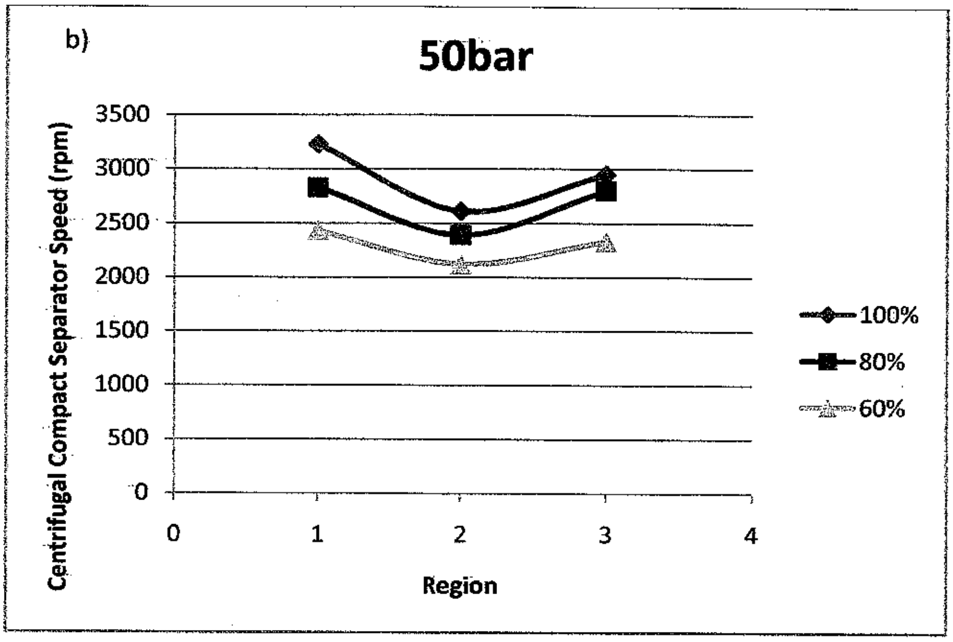


Figure 10: Rotating Blade (rpm) Vs Compressor Speed (%)

From figure above, it is proven that higher compressor speed result in faster rotation speed (rpm). This is because the compressor speed is the key that trigger or control the speed of the blade inside the compact separator. The velocity produce by the compressor give significant impact on the rotation per unit of the blade. From Equation 5, angular speed is one of the parameter that affecting the radial particle velocity. The higher value of angular speed results in higher radial particle velocity. In this project, radial velocity indicates the difficulties of water particle to be separated from the natural gases. The higher value of radial velocity results in easier separation process to take place. This is applicable for all those three pressures tested; 60 bar, 50 bar and 40 bar.

The rotation of the blade will not be constant during the experiment. The free water inside the natural gases will block or reduce the speed of the blade. This is when the separation process takes place. The speed of the compact separator is reduced due to resistance while rotating from the free water that is in contact with the blade thus separates the water particles to the wall. The water particle collected will drain to knockout drum from opening at the side of the separator.





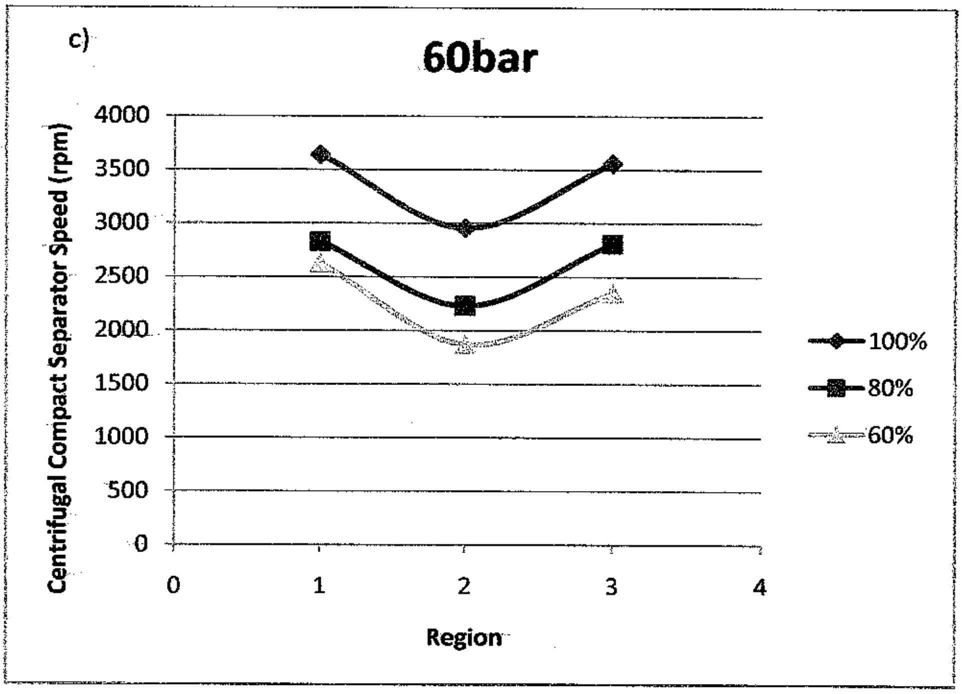


Figure 11: Centrifugal Compact Separator Speed (rpm) Vs Region (1-Before Water Addition. 2-During Water Addition. 3-After Water Addition) a) 40 bar, b) 50 bar, c) 60 bar

All pressure with different compressor speed share the same pattern of the graph. Figure 11 shows the effect of speed of the blade inside the compact separator with the region of event. Region 1 is before water addition into the stream, region 2 is where the water injected into the stream. At this region we can observe that the speed of the blade will reduce almost 30% of its initial speed. The differences of initial speed and during water addition able indicated amount of water separated. This is because the slower the rotation of the blade portrays high resistance for the blade to rotate which mean more water droplet is in contact with the blade. These bring the effect of density of gas to the separation efficiency.

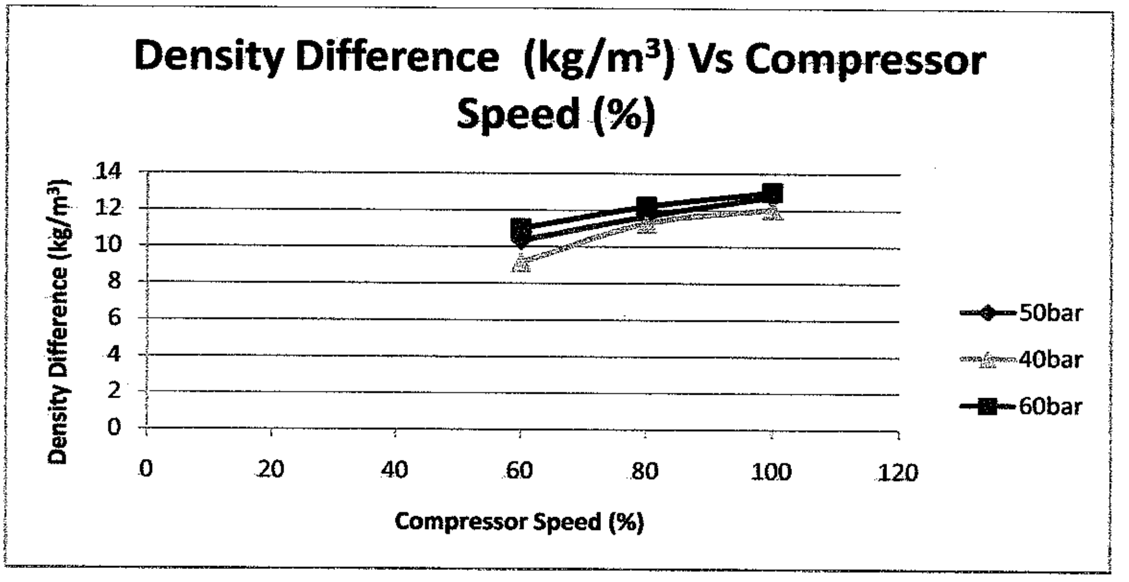


Figure 12: Density Difference (kg/m^3) Vs Compressor Speed (%)

The density difference between the particle and medium relate with the radial velocity. Figure 10 shows relationship between the compressor speed and density difference. Higher density differences result in higher radial velocity which indicates the particles are easier to separate. The graph indicates higher compressor speed produce higher density difference. This conclude that higher compressor speed ensure higher density difference which result in easier to separate and lead to better separation efficiency.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Theoretically, it is proven that inlet gas velocity give significant impact to the separation efficiency. From the discussion part, it is proven that as inlet velocity increase, the speed of centrifugal compact separator and density difference also increase resulting in easier separation which lead to higher moisture (free water) separation efficiency. The project shows that it is feasible to remove free water from natural gas in theory. But from the data archive, none of the pressure with different compressor speed able to archive 99.9% separation efficiency. Practically, it is difficult to separate and additional equipment might able to improve separation the efficiency as example is installing expansion. This will change the phase of the water vapor or free water to increase separation efficiency using high centrifugal force.

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APPENDICES

Table 9: All Experiment Data

Pressure (bar)	Water Load (%)	Compressor speed (%)	Gas Mass Flow (kg/hr)
60 bar	30	100	2737.98
		80	2363.3
		60	1725.63
	20	100	2194.26
		80	2225.4033
		60	1764.9433
	10	100	2036.65
		80	2269.14
		60	1764.9433
50 bar	20	100	2367.4367
		80	1955.9067
		60	1297.203
	30	100	2321.61
		80	1899.6
		60	1459.96
	10	100	2361.29
		80	1842.92
		60	1297.3
40 bar	30	100	1787.78
		80	1225.77
		60	1062.135
	20	100	1766.185
		80	1232
		60	1051.1967
	10	100	1678.6267
		80	1469.62
		60	933.64

Table 10: Gas Density Difference

Pressure (bar)	Water Load (%)	Compressor speed (%)	Mixed Temperature (°C)	Gas Density (kg/m3)	Mixed Gas Density (kg/m3)	Density Difference (kg/m3)
60 bar	20	100	35	37	50.41	13.41
		80	35	36	48.21	12.21
		60	35	36.9	48.2	11.3
50 bar	20	100	35	29.16	41.92	12.76
		80	35	29.93	41.61	11.68
		60	35	30.759	41.11	10.351
40 bar	20	100	35	23.457	35.51	12.053
		80	35	23.914	35.2	11.286
		60	35	24.429	33.58	9.151

Table 11: Blade Speed Data

Pressure (bar)	Water Load (%)	Compressor speed (%)	Before Water Addition (rpm)	During Water Addition (rpm)	After Water Addition (rpm)
60 bar	20	100	3640	2955	3560
		80	2830	2230	2810
		60	2630	1870	2350
50 bar	20	100	3230	2610	2950
		80	2830	2390	2800
		60	2430	2120	2330
40 bar	20	100	2560	2390	2480
		80	1990	1850	1890
		60	1870	1760	1860